MilliKelvin Facility

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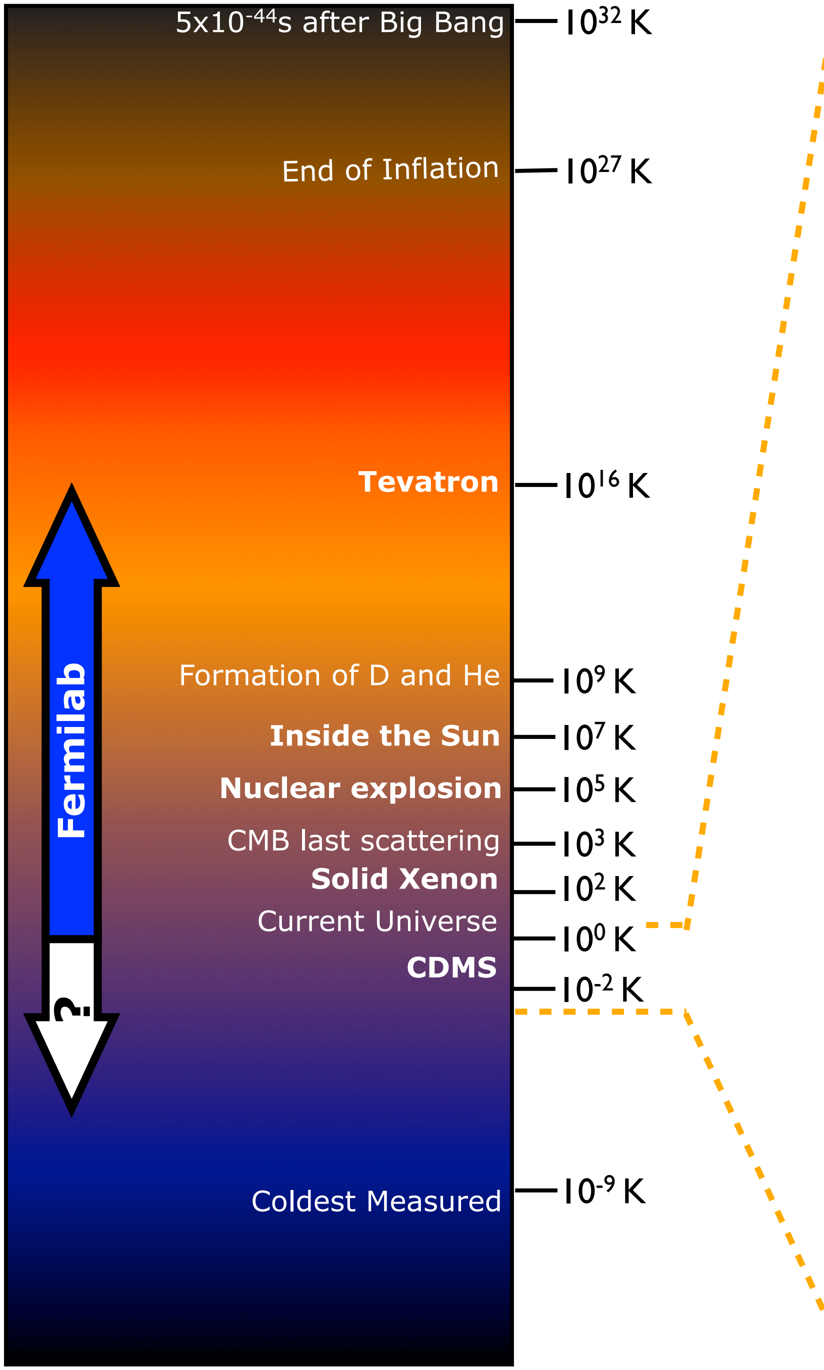
Fermilab

Fermilab Detector R&D Retreat
5 May 2011

Big Picture



In the sub-Kelvin regime, the atomic thermal motions, vibrations of material and electron temperatures are substantially reduced and hence the true nature of the atomic quantum effects become manifest.

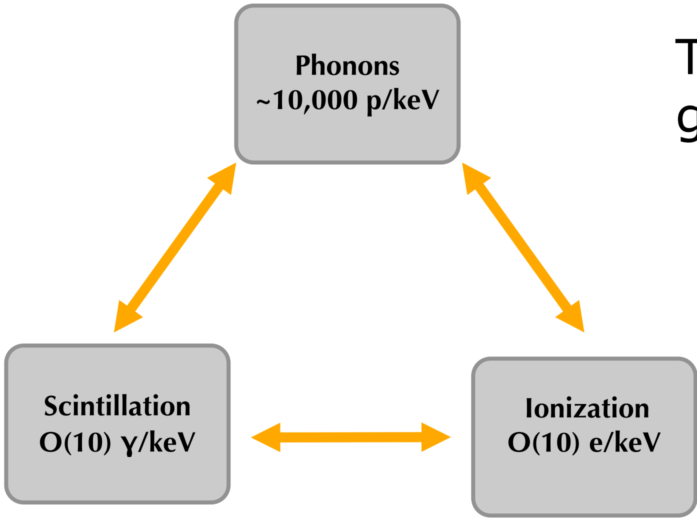
- Superconductivity
- Quantum hall effect
- Exotic phase transitions
- Heavy fermions

<u>Physics topics</u>

- Dark Matter search
- Neutrino physics
  - beta endpoint
  - neutrinoless double-beta decay
- Rare nuclear decays
- High resolution X-Ray spectroscopy
- Ultra-low background photon sensors
- Cosmic Microwave Background
- X-Ray and UV to IR Astrophysics

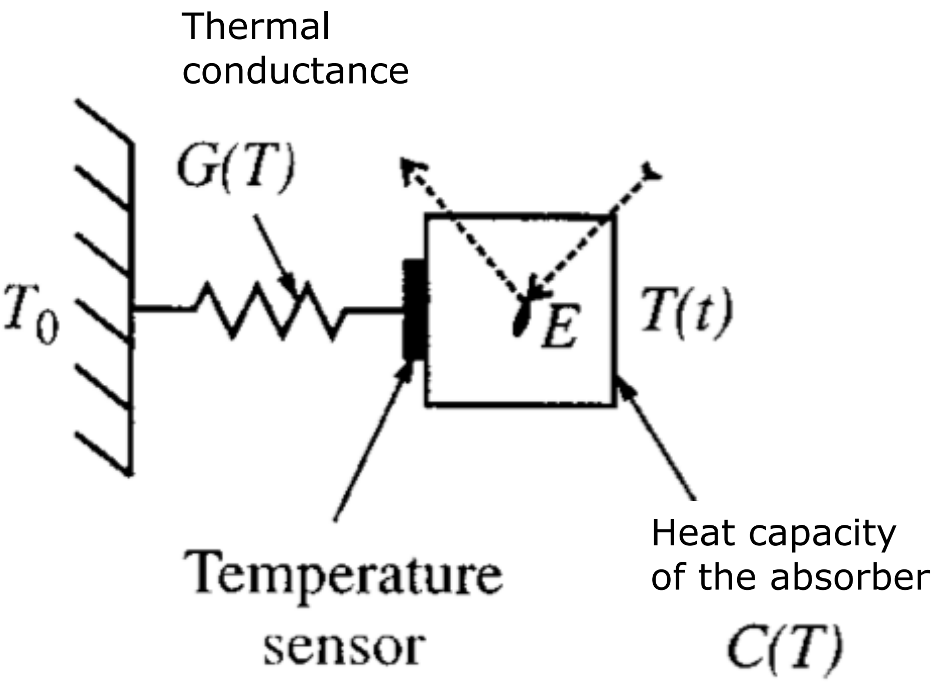
The lowest temperature at Fermilab > 2 Kelvin

Thermal Detectors



Typically 70~90% of energy of particle interactions goes into heat (phonon) channel.

$$\Delta T = \frac{E}{C(T)} exp(-t/\tau), \ \tau = C(T)/G(T)$$



Heat capacity at low temperature

$$T \ll \Theta_D$$

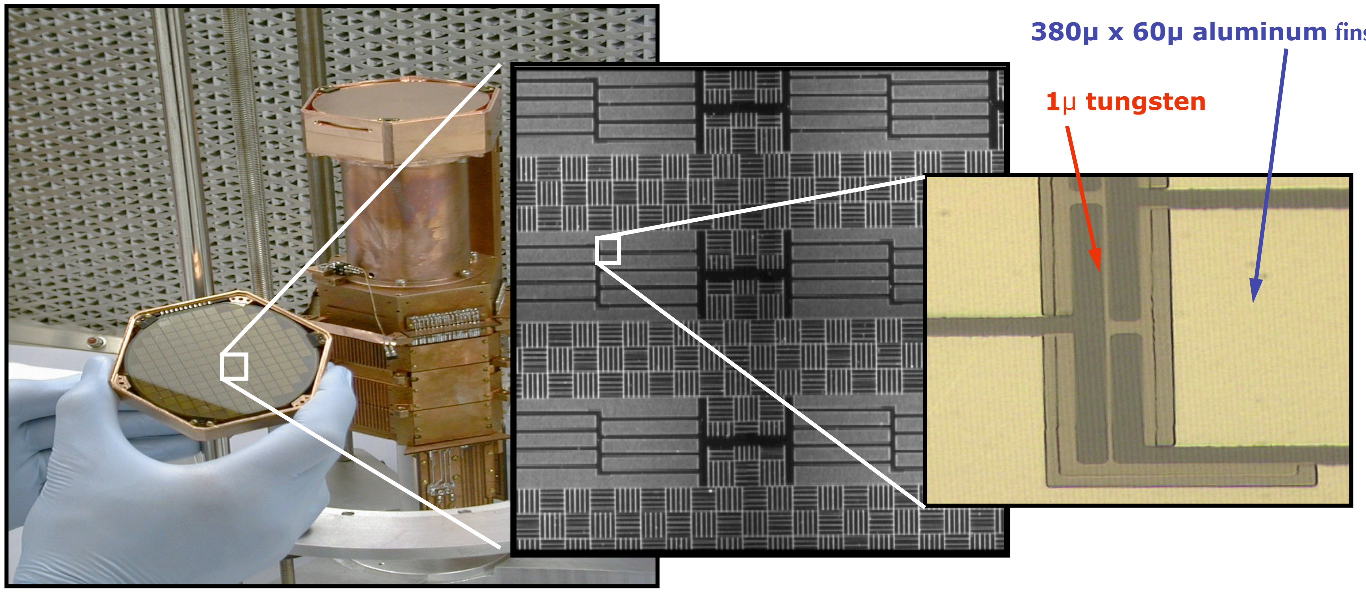
$$C(T) = \frac{12\pi^4}{5} Nk \left(\frac{T}{\Theta_D}\right)^3$$

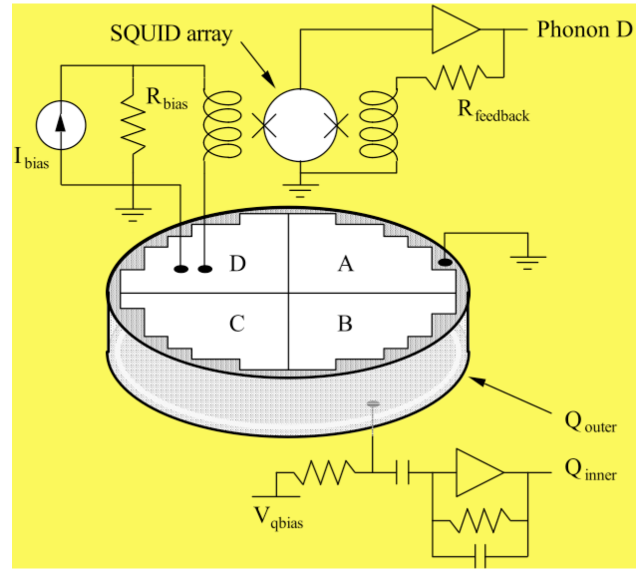
$$= 3.2 \times 10^{12} \ m \ T^3 \ [\mathrm{eV/K}]$$

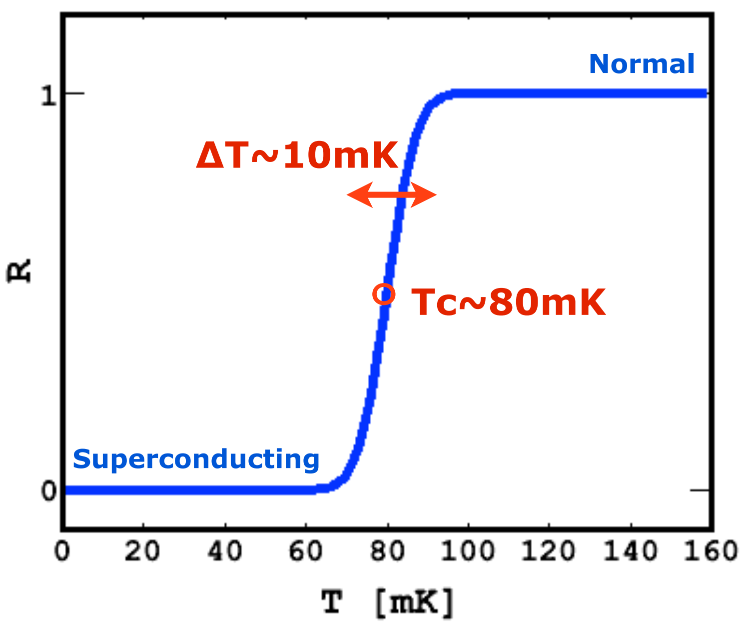
Energy Fluctuation

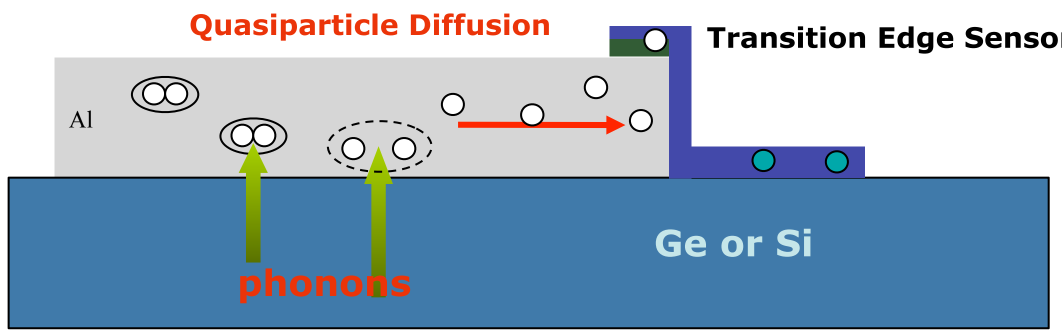
$$\sigma = \xi \sqrt{kT^2 C(T)}$$

Athermal Phonon Detector





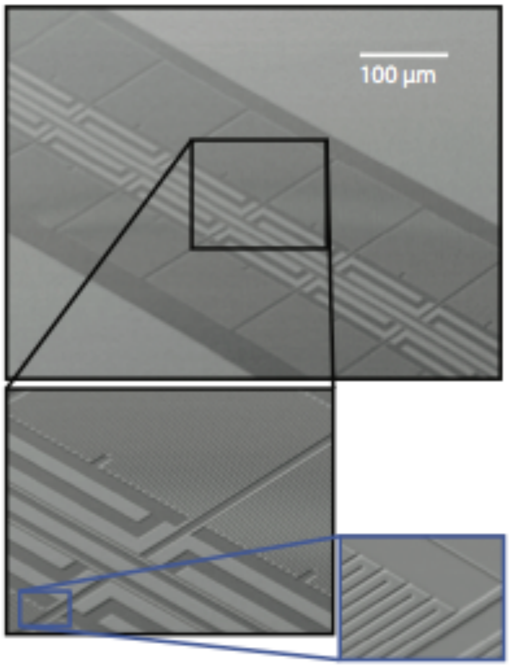


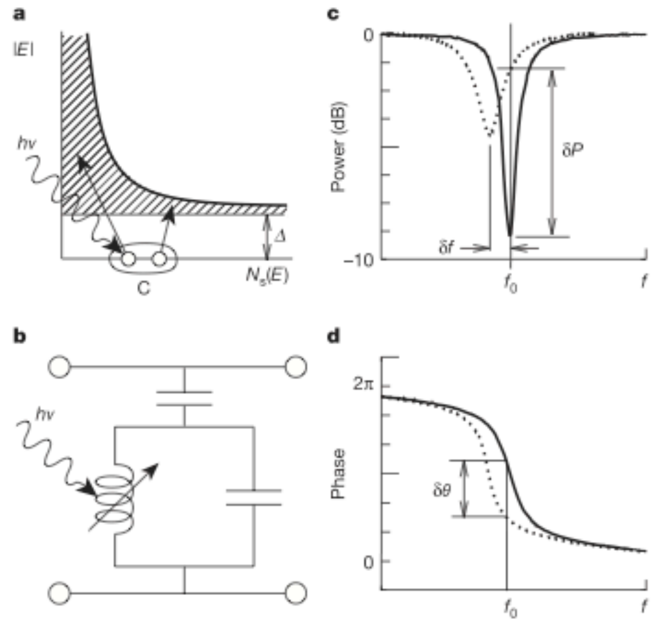


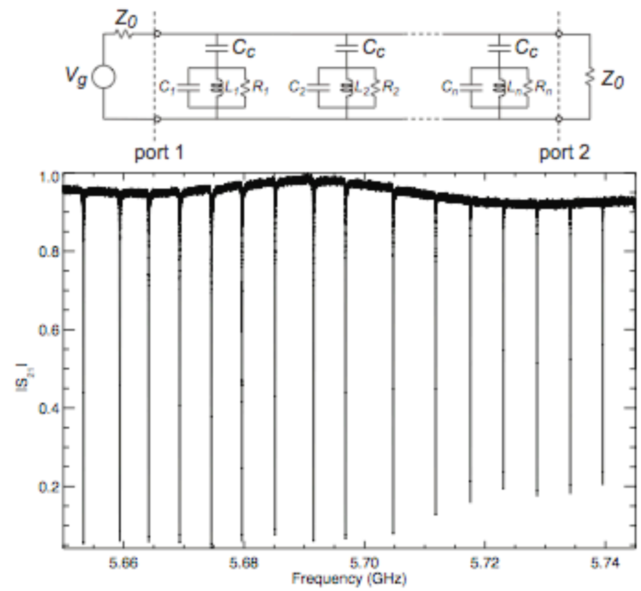
The athermal phonon detection technology shows wide range of applications:

- dark matter search
- 0v2b-decay
- axion search
- X-ray telescope …

MKID IR Camera R&D: Juan Estrada



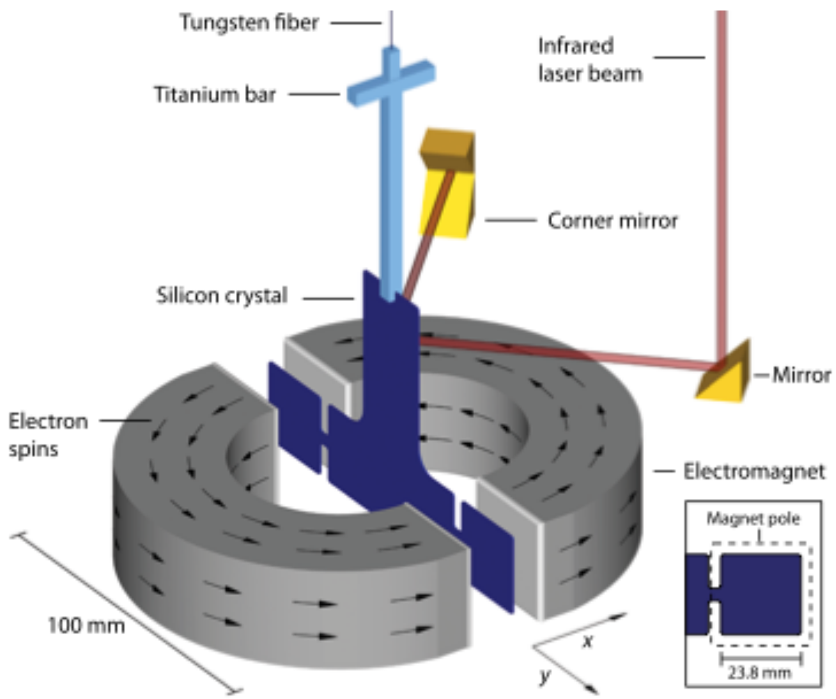




- Superconducting band gap: ~100ueV
  - → huge population of quasiparticles for a given quantum energy *hv*
- Kinetic inductance and microwave surface resistance sensing technology
- Many resonators with slightly different frequencies → multiplexing
- Large array detector development is possible
- We are interested in various application of this technology

Torsion Pendulum

Fritz DeJongh, Jason Steffen, Chris Stoughton



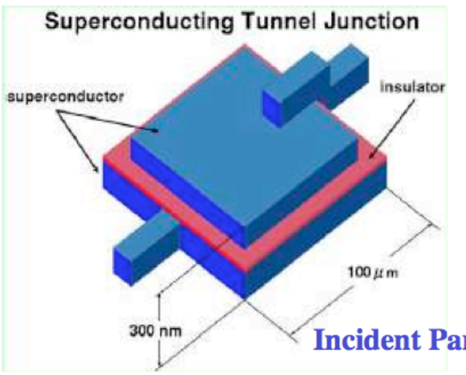
Hoedl at al,
Search for Axion-Mediated Force

- Look for axion coupled forces, departures from GR, or changes in fundamental constants
- Thermal white noise scales as $\sqrt{T}$
- Q improves at low T
- R&D and tests of designs to cool fiber to 40 mK

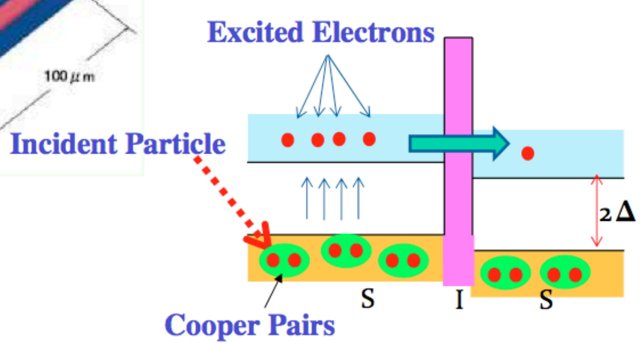
Superconducting Photon Detector R&D

Superconducting Tunnel Junction (STJ) Detector R&D Proposal
by Japanese Collaboration (Prof. Shinhong Kim; Tsukuba University + 3 Institutions)

- Superconductor / Insulator / Superconductor Josephson Junction



At the superconducting junction, excited electrons over their energy gap go through tunnel barrier by a tunnel effect.
By measuring the tunnel current of electrons excited by an incident particle, we measure the energy of the particle.



STJ Energy Resolution

$$\delta E_{FWHM} = 2.35\sqrt{(1.7\Delta)FE}$$

Δ : Band gap energy
F: Fano factor
E: Incident particle energy

Using Hf as a superconductor, the number of quasi-particles is N=30meV/1.7Δ=882

ΔE/E < 1/√N=1/√882=3.4% @30meV

No paper on Hf–STJ test in the world.

	Si	Nb	Al	Hf
Tc [K]		9.23	1.20	0.165
Δ [meV	1100	1.550	0.172	0.020
Hc [G]		1980	105	13

Tc : Critical Temperature
Operation is done at a temperature of 1/10 of Tc
Hc : Critical Magnetic Field

March 24, 2011
Shinhong Kim

Letter of Intent

Superconducting Photon Detector R&D

Motivation

We, a collaboration of University of Tsukuba, KEK, JAXA/ISAS, SNU, propose to search for neutrino radiative decays by fitting the cosmic infrared background energy spectrum with the energy spectrum of photons from the neutrino radiative decay. Detection of neutrino radiative decay enables us to measure an independent quantity of the mass-squares differences of different generation neutrinos determined by various neutrino oscillation experiments. Thus we can determine the neutrino mass itself from these two independent measurements, the neutrino oscillation and the neutrino decay.

The neutrino decay photon energy spectrum has a sharp edge at high energy end. To detect this sharp edge, we need a micro-calorimeter of infrared photons with high energy resolution. The requirement of energy resolution is 3% for photon energy of 25 meV.

To satisfy this requirement, we are developing a Superconducting Tunnel Junction (STJ) detector as a photon detector. At the superconducting junction of STJ, excited electrons over their energy gap go through tunnel barrier by a tunnel effect. By measuring the tunnel current of electrons excited by an incident particle, we measure the energy of the incident particle. The smaller the superconductor energy gap is, the better the energy resolution is. So we use Hf (hafnium) as a superconductor material instead of Nb which is the most popular superconductor material as used in the STJ detectors. Hf has about one hundredth energy gap (0.020meV) of Nb energy gap (1.55meV). We started R&D of HF-STJ detector in 2006.

R&D Status and Plan

We have produced many samples of Hf-STJ with the sputtering and etching machines at KEK, and have measured the characteristics of the Hf-STJ at University of Tsukuba, using a He_3/He_4 dilution refrigerator borrowed from a group of Low Temperature Material Science at University of Tsukuba in 2008 which achieved 49mK on July 2009. Since the critical temperature of Hf is 160mK, we need 20-50mK for the Hf-STJ detector operation.

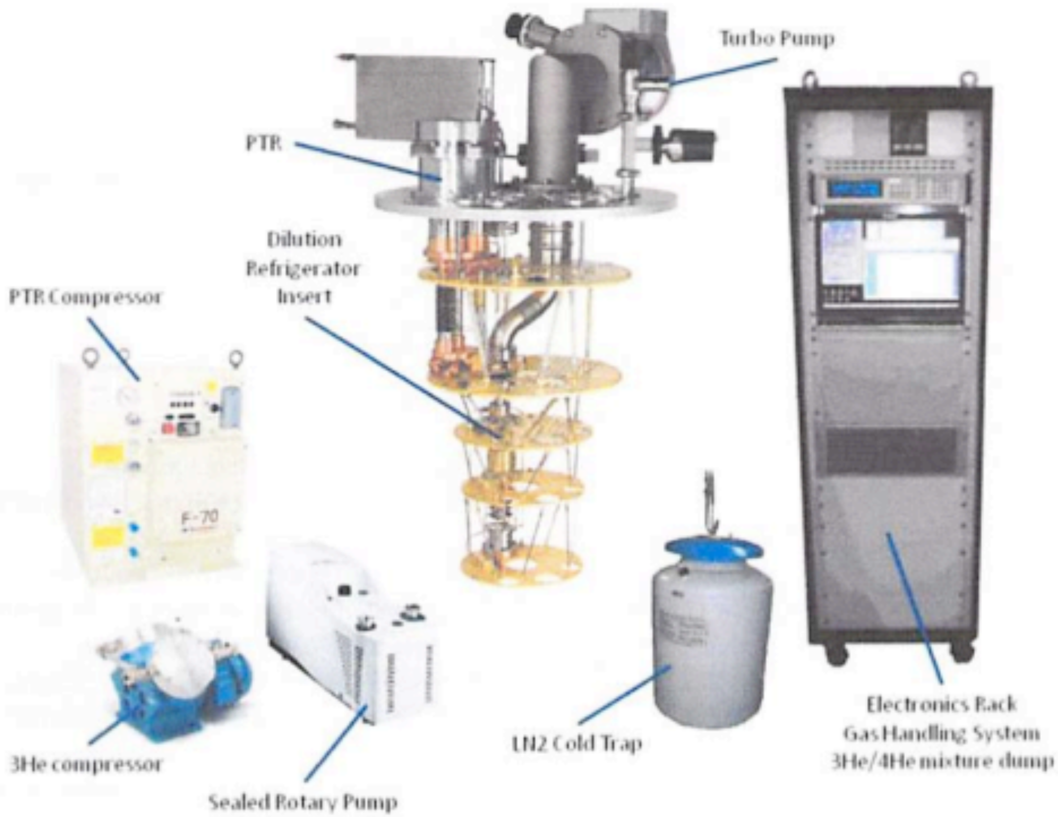
At the end of 2010, we observed that a Hf-STJ detector had Josephson currents which disappeared by applying a magnetic field of two gauss. In the next step, we will see a signal from the Hf-STJ detector by injecting laser photons. To do so, we need to reduce the large leakage current and the large noise.

We asked a Fermilab group to join this Superconducting Photon Detector R&D especially on the development of low-noise electronics workable at very low temperature around 1K. If the Fermilab group will join it, we will collaborate on this R&D using Fermilab Milli-Kelvin Facility. This Facility will give us a very useful environment for the test of the superconducting photon detector.

- **They want Fermilab's help in low noise electronics development**
- **Potential US-Japan collaborative project starting from FY12 (~$100K/year)**

Fermilab
MilliKelvin User Facility

Dilution Refrigerator: OXFORD Tritron^{TM} 400/200

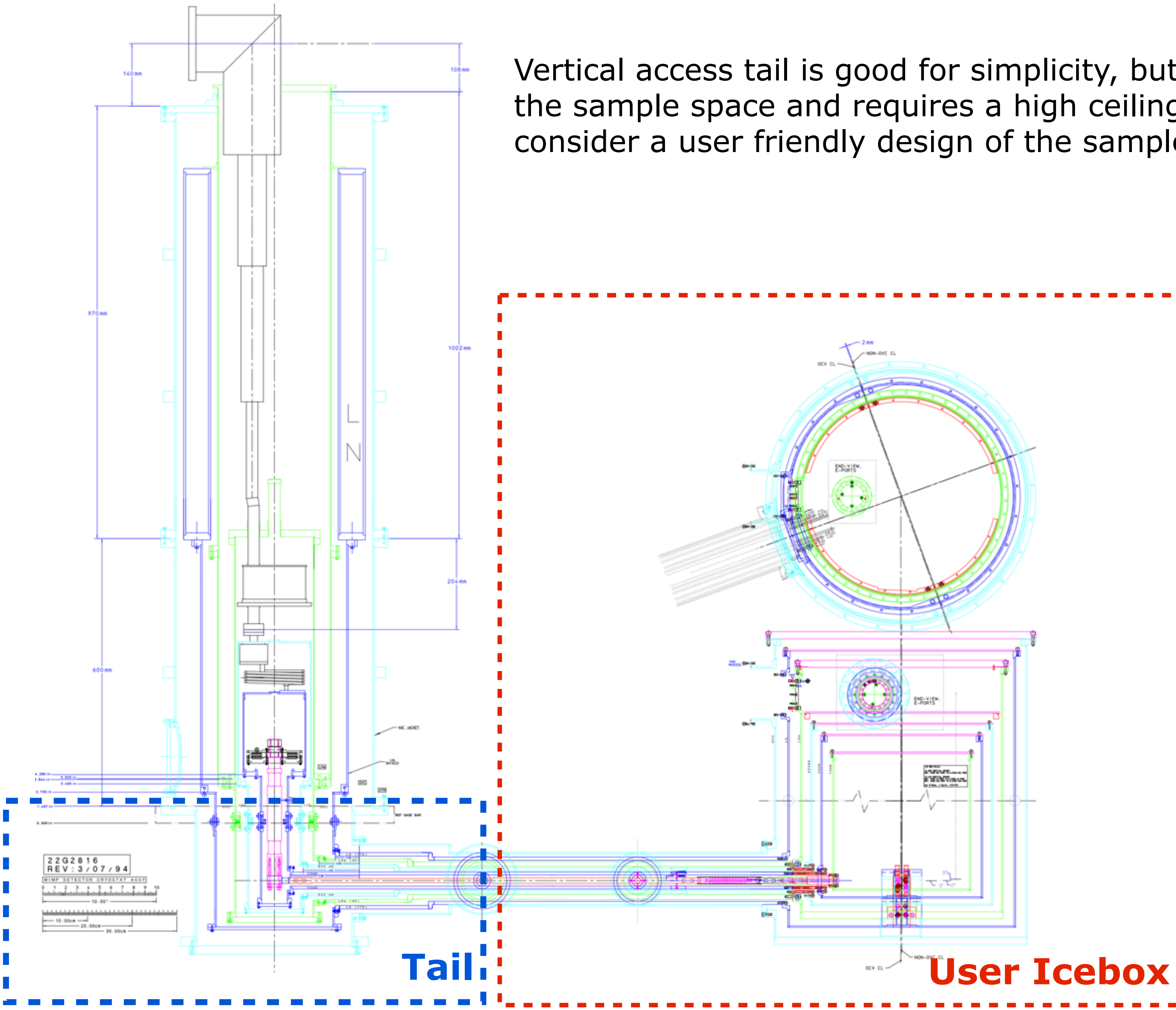


- Cryogen-free operation
- High cooling power
  400/200uW @100mK
- Low vibration pulse tube fridge
- Custom made refrigerator tail design
- 10mK base temperature
- Fast cool-down times: < 24hr
- Automatic gas handling system
- Built-in cryogenic cold trap technology
- Possible option with SC magnet to 15T
- 3~6 months of delivery leading time

Price Tag: \$500K(\$400K)

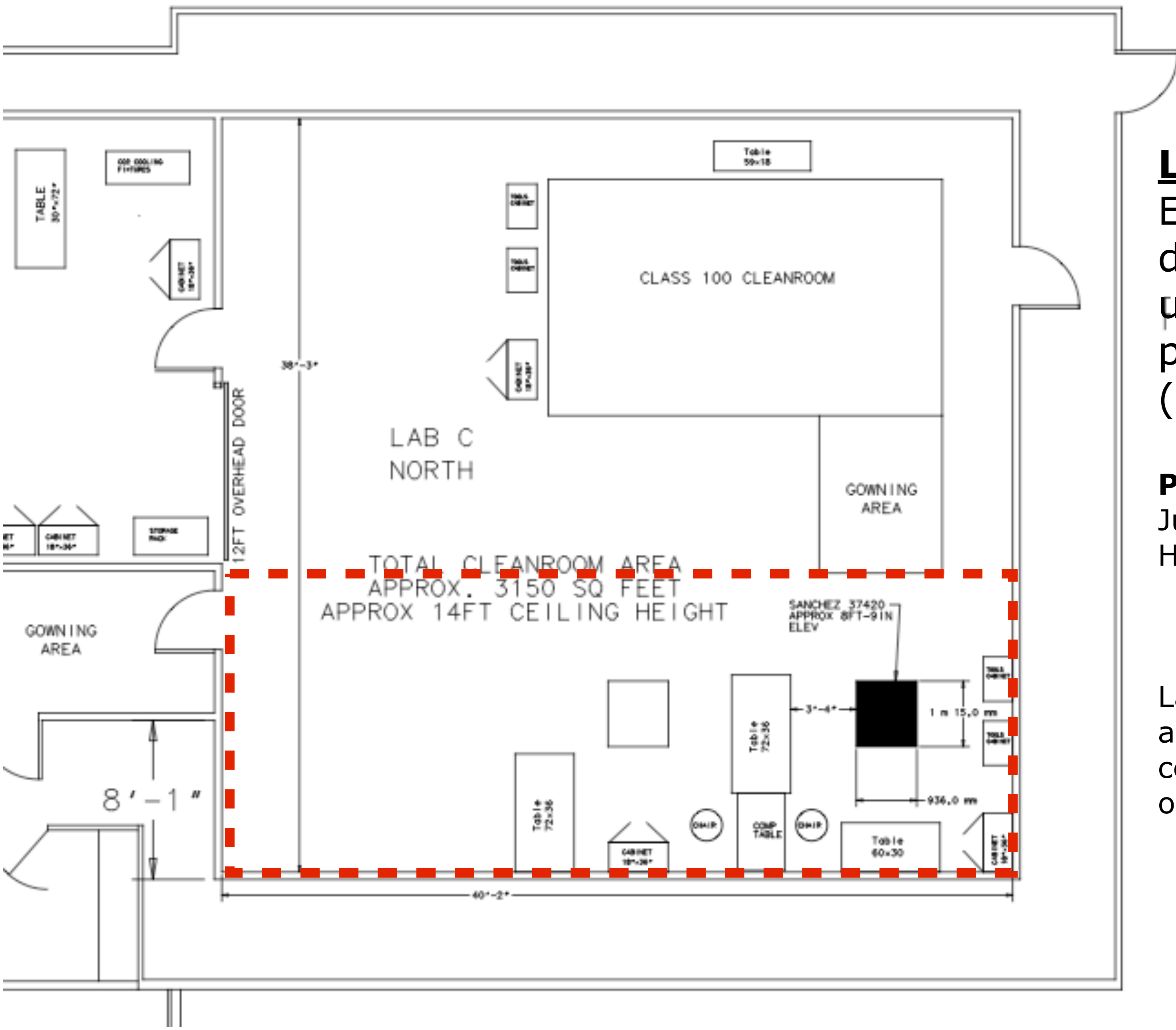
We will check with other vendors as well

User Friendly Sample Space Access



Vertical access tail is good for simplicity, but bad to access the sample space and requires a high ceiling. We will consider a user friendly design of the sample space.

Potential Instrumentation at Lab-C



<u>Lab-C South</u>

Enough space for a dilution refrigerator unit, ice-box and preparation room. (14FT ceiling height)

Proponents:
Juan Estrada, John Krider, Herman Cease

Lab-3 clean room might be another option, but lower ceiling height (12FT) and lack of local tech/eng resources

MilliKelvin User Facility

- The cryostat design will require about a few months of engineering and design effort. Fabrication cost would depend on material limitations and special features which are the subject of engineering design.

- We do not consider cosmogenic or radiogenic background shielding in the initial facility setup. We may consider RF shielding of the lab-space and magnetic shielding of the default icebox design.

- A user’s manual of the facility will be developed to standardize the user’s device design. We will follow the policy of other Fermilab User facilities.

Current Fermilab Experts of mK

A new Generation

Summary

- We have just started discussions about instrumenting a low temperature laboratory at Fermilab. We found there are increasing activities requiring milliKelvin facilities amongst the Fermilab users.

- We do have experts who can successfully build/operate the facility.

- It's a big investment and a new endeavor, but worthwhile for Fermilab's future.

Any buried idea in your "Forget about it"-folder → yoo@fnal.gov